MULTI-TONE SIGNAL TRANSMISSION METHODS AND APPARATUS

Related Applications

The present invention claims the benefit of the filing date of U.S. Provisional Patent Application S.N. 60/291,071 filed May 15, 2001.

Field of the Invention

The present invention relates to communications systems and, more particularly, to methods and apparatus for communicating information using multi-tone signals, e.g., orthogonal frequency division multiplexed (OFDM) signals.

Background

The use of multi-tone signals for the communication of information has been proposed for quite some time. In such systems, a plurality of tones are used to communicate symbols in parallel, with the total bandwidth between a transmitter and receiver device being a function of the number of tones being used to communicate the information.

Generally, a multi-tone signal includes N (N>0) complex symbols modulated on N distinct tones simultaneously in a symbol duration T:

$$s(t)=\sum_{k=1}^{N} A_k \cos(2\pi f_k t+\theta_k),$$ for t=[0,T].

In the above equation, θ_k and A_k are respectively the phase (in radians) and amplitude of the complex symbol to be transmitted on tone k, and f_k is the frequency of tone k. t is the time variable. A multi-tone signal comprises a plurality of single-tone signals, where each single-tone signal is a periodic signal. In a practical system, the periodic signals are transmitted for a symbol duration T, which is a finite time interval.

An OFDM signal is an example of the multi-tone signal with each distinct tone k representing a different subcarrier. In an OFDM signal the distinct tones which are used to form the OFDM signal are orthogonal over the symbol duration.

Fig. 1 illustrates a known OFDM transmission system 1. In the known system, for each period in which a symbol is to be transmitted, a digital complex symbol generator 2 generates a vector of digital complex symbols. The vector includes, e.g., one symbol per OFDM tone to be used. The vector of complex symbols are then transformed into a vector of complex time domain samples corresponding to a symbol period by a Fourier transform operator 3, e.g., a discrete or fast Fourier transform circuit. The time domain samples represent the discrete samples of the baseband signal to be transmitted during a symbol transmission period. This signal is essentially the sum of

one or more sinusoid component signals, e.g., the OFDM tones. A single cyclic prefix is generated for the signal to be transmitted during a symbol transmission period. The cyclic prefix is added by the cyclic prefix generator 4 to the vector of time domain samples supplied by the Fourier transform operator 3. Generally, the cyclic prefix is usually a copy of the last few samples in the vector of the time domain samples and will therefore include all the OFDM signal's sinusoid components, e.g., tones. After the cyclic prefix is appended to the beginning of the samples supplied by the fourier transform operator 3, the signal samples pass through a filter 5. The filter 5 is used to limit out of band spectral emissions. The filtered samples are then converted to an analog signal by a digital to analog converter 6. The analog signal is then mixed with the carrier frequency by mixer 7 to generate a passband signal. The passband signal is then power amplified by amplifier 8 and transmitted to a communication channel through a single antenna 9.

Accordingly, in the known system shown in Fig. 1, a periodic sinusoidal signal to be transmitted is generated in the baseband, a cyclic prefix is added in the baseband, and then the signal is mixed to the passband prior to OFDM signal transmission.

While the concept of using a multi-tone or OFDM signal to communicate information is relatively well understood, the existing techniques for transmitting such a signal tend to be inefficient in terms of power utilization. The power inefficiency results from the multi-tone signal being a sum of a plurality of single tone

signals, which normally leads to a high peak-to-average ratio in the resultant multi-tone signal. As a result, there is a need for improving the transmission techniques of multi-tone signals, e.g., OFDM signals. It is desirable that at least some new transmission techniques increase the power efficiency of multi-tone signals thereby making them better suited for use in systems such as wireless communication networks where long battery life and inexpensive power amplifiers of wireless devices are highly desirable.

Summary

The present invention is directed to methods and apparatus for generating and transmitting multi-tone signals, e.g., OFDM signals in accordance with the present invention.

In accordance with the present invention, a plurality of tones are used to communicate information represented by symbols, in parallel. One symbol is transmitted per symbol transmission period for each tone used. In accordance with various aspects of the present invention, separate analog signals, e.g., N periodic signals, one per tone being used, are generated in parallel. Each separate analog signal may be generated from a different digital complex symbol.

Generation of the separate analog signals corresponding to a tone comprises generating a periodic signal corresponding to a digital complex symbol, generating a prefix for the generated periodic signal,

filtering the periodic signal with prepended prefix and transmitting the filtered signal.

In many embodiments, the periodic signals used to represent symbols are sinusoidal waves. However, in some embodiments the periodic signals are square waves. Each of the N generated periodic signals corresponds to a different tone. In accordance with the present invention, each periodic signal may include in addition to a component at its fundamental frequency, e.g., the frequency of the tone, one or more high order harmonics. The high order harmonics include, e.g., signal components at integer multiples of the fundamental frequency.

In various embodiments of the invention, the period signal representing the symbol to be transmitted is generated in the passband. A prefix, e.g., cyclic prefix is then generated and added to the periodic signal in the passband. The passband corresponds to the range of frequencies in which the information is transmitted into the communications channel while the baseband corresponds to the frequency band of the modulating signals used in a transmitter.

This approach is in sharp contrast to known OFDM signal generation techniques such as that shown in Fig. 1 where the periodic sinusoidal signal to be transmitted is generated in the baseband, a cyclic prefix is added in the baseband, and then the signal is mixed to the passband prior to OFDM signal transmission.

Since prefixes are generated separately for each tone, while the prefixes for N tones being transmitted during the same symbol transmission period will have a prefix of the same duration, the content of the prefix will vary from tone to tone for a given symbol transmission period. This, is in sharp contrast to the prior art OFDM system discussed above, wherein the signals corresponding to different tones are effectively combined prior to prefix generation resulting a single prefix being generated for a signal corresponding to multiple tones.

Various features of the present invention are directed to novel techniques for generating prefixes for signals corresponding to individual tones and to provide for a relatively smooth signal transition between periodic signal portions used to represent symbols which are transmitted sequentially, e.g., in consecutive symbol transmission periods. In order to achieve the desired smooth signal transitions between transmitted periodic signals representing consecutive symbols transmitted using a particular tone, each prefix is divided into multiple parts in accordance with one feature of the present invention. The different parts of a multi-part prefix are generated from different data and/or using different generation techniques.

Accordingly, the prefix generation techniques of the present invention differ from the known systems not only by the fact that a different prefix is generated for each tone being used but also by the fact that, at least in some embodiments, prefixes are multi-part prefixes as opposed to single part prefixes.

In particular embodiments, the first part of a cyclic prefix is generated from a periodic signal representing a current symbol, e.g., to cyclically extend the periodic signal representing the current symbol. However, the second part of the prefix is generated to smoothly, e.g., continuously, connect the end of the periodic signal portion representing a previous symbol and the first part of the cyclic prefix generated for the current symbol. Accordingly, the first part of a multi-part prefix represents a cyclic prefix portion while the second part of the prefix represents a continuity portion.

By avoiding abrupt signal transitions between signals transmitted during consecutive symbol transmission periods through use of a multi-part prefix, out of band spectral emissions can be reduced and/or eliminated as compared to cases where abrupt changes occur at the transition between symbol transmission periods.

To insure a smooth signal transition, in some embodiments the 2^{nd} part of a multipart prefix is generated as a function of the periodic signal representing the preceding symbol and the 1^{st} part of the prefix generated from the periodic signal portion representing the current symbol. As discussed above, the 1^{st} part of a multi-par prefix is generated from the periodic signal portion representing a current symbol. Thus, in accordance with the present invention, multi-part prefixes are generated as a function of the periodic signal representing the current symbol to be transmitted and the periodic signal representing the preceding symbol to be transmitted.

Various exemplary techniques for generating multi-part prefixes in accordance with the present invention are discussed below.

The independent generation and processing of signals corresponding to different tones of a multi-tone signal provides advantages in terms of power efficiency over the known system since the individual signals tend to have a better peak to average power ratio than the signal of the known system which corresponds to multiple tones.

In accordance with one particular feature of the present invention, different antennas are used to transmit signals corresponding to different tones of a multi-tone signal during the same symbol transmission period. The individual transmitted signals combine in the communications channel, e.g., air, to form the multi-tone signal which is received by a receiver, e.g., using a single antenna. In one embodiment, a separate antenna is used to transmit each tone of a multi-tone signal. Accordingly, in such an embodiment, where N tones are used in a multi-tone signal, N antennas are used to generate N separate signals. In other embodiments, tones are combined into groups, e.g., tone subsets, for transmission purposes by multiple antennas. For example, assuming a multi-tone signal with N tones is to be transmitted, the signals to be transmitted may be combined into M distinct signals, with the M signals being transmitted using M antennas where $N>M>1$.

Numerous additional features and embodiments relating to the generation and transmission of multi-tone signals, e.g., OFDM signals, are discussed in the detailed description which follows.

Brief Description of the Figures:

Fig. 1 illustrates a known OFDM transmission system where a single cyclic prefix is generated for each symbol period and wherein a single antenna is used to transmit an OFDM signal corresponding to multiple tones.

Fig. 2 is a flow chart illustrating a method of generating and transmitting a multi-tone signal in accordance with an exemplary embodiment of the present invention.

Figs. 3A and 3B illustrate exemplary systems of the invention which can generate and transmit multi-tone signals in accordance with the method illustrated in Fig. 2.

Figs. 4 and 5 illustrate periodic signals generated in accordance with the present invention.

Fig. 6 illustrates two signals, each including a prefix and periodic signal portion, corresponding to one of N subcarrier tones of a multi-tone signal.

Fig. 7 illustrates a signal of one symbol duration, including a two part prefix and a periodic signal portion in accordance with the invention.

Figs. 8 and 9 illustrate different methods of generating a two-part prefix in accordance with various embodiments of the invention.

Figure 10 illustrates the constellation corresponding to two consecutive symbol durations generated and transmitted in accordance with one embodiment of the present invention.

Fig. 11 illustrates the construction of the first symbol in a dwell and the determination of an amount of phase rotation to be used.

Detailed Description

Fig. 2 is a flow chart illustrating a method 20 of generating and transmitting multi-tone signals in accordance with the invention. As illustrated, the method 20 starts in START step 22, e.g., with a signal generation and transmission system of the present invention being initialized. Operation proceeds from step 22 to step 24, wherein the digital data to be broadcast is received. Next, in step 26, from the received data a plurality of digital complex symbols which are to be transmitted in the same symbol duration are generated. One digital complex symbol is generated for each tone of the multi-tone signal to be broadcast. The plurality of digital complex symbols generated in step 26 are processed in parallel in steps 28, 30, 32, and 34 to generate analog signals, which are suitable for transmission using different tones of a multi-

tone signal. Transmission may be over a communications channel such as the air.

In accordance with the present invention, each analog signal which is broadcast over the communications channel includes a periodic signal portion and a prefix signal portion. In step 28, the periodic signal portion of an analog signal is generated from the digital complex symbol. Then, in step 30, the prefix signal portion of an analog signal is generated. The prefix portion and the periodic signal portion of the generated analog signal to be broadcast are combined, e.g., the periodic signal portion is appended to the beginning of the prefix portion, in step 30 or subsequent thereto, to create the analog signal to be broadcast. Then, in step 32, which is an optional filtering step, filtering is performed on the analog signal. With filtering completed, the analog signal including the periodic signal portion and prefix signal portion is transmitted in step 34 using an antenna. As will be discussed in detail below, in one embodiment of the invention, the analog signals corresponding to each tone of a multi-tone signal are transmitted in parallel using separate antennas, e.g., one per tone. The transmitted analog signals of all the tones are combined in the channel itself to form the multi-tone signal. Alternatively, prior to signal transmission, the analog signals corresponding to a plurality of different subcarriers, e.g., tones, can be combined for transmission by a single shared antenna. In accordance with the present invention, depending on the degree of multiplexing before transmission of analog subcarrier signals, the number of antennas used to broadcast a multi-tone signal may range anywhere from 1 to

N where N is the number of tones in the multi-tone signal. In several embodiments, as will be discussed below, a plurality of antennas are used to transmit the different groups of tones which comprise a multi-tone signal. In such a case, the analog signals of a multi-tone signal broadcast using different antennas are effectively combined in the communications channel through which the subcarrier signals are broadcast.

Multiple antennas are used for transmission for purposes of power efficiency as opposed to avoid signal interference or to increase channel diversity as used in a known wireless communication system. Accordingly antenna spacing can be extremely close at the transmitter making multiple antennas in a portable device possible. Antenna spacing at a transmitter in terms of physical distance can range e.g., anywhere from one half the wavelength of any one of the tones (e.g., the tone having the shortest wavelength of in a set of N tones) being transmitted to as little as thousands of a wavelength or even less. Accordingly, in various embodiments antenna spacing, **A**, is as follows: Exemplary embodiment 1) $\mathbf{A} < 1/2\lambda$; Exemplary embodiment 2) $\mathbf{A} < 1/100\lambda$; and Exemplary embodiment 3) $\mathbf{A} < 1/1000\lambda$, where λ is the wavelength of the tone in a multi-tone signal being broadcast, which has the shortest wavelength. **A** may be expressed in meters or feet or any other common unit of distance.

Steps 24-34 are repeated so that data can be transmitted over multiple symbol durations. Thus, steps 24-34 are normally performed for each symbol duration

resulting in the transmission of data using multi-tone signals over a period of time.

Fig. 3A illustrates an exemplary multi-tone signal generation and transmission system 100 of the present invention. The system 100 can be used to implement the method 10 shown in Fig. 2. As illustrated, the system 100 includes a digital complex symbol generator 102 for generating, from received data to be broadcast, digital complex symbols, one for each subcarrier frequency f_k, where k extends from 1 to N. The system 100 also includes a periodic signal generator module 104, prefix generator module 106, filter module 108, and an antenna array 110 used to broadcast signals into communications channel 112, e.g., the air.

The periodic signal generator module 104 includes an array of N periodic signal generator circuits 120, 120', 120'', one per subcarrier frequency f_k. Similarly, the prefix generator module 106 includes an array of N prefix generator modules 122, 122', 122'' while the filter module includes an array of N filters 124, 124', 124''. In the Fig. 3A embodiment the antenna array 110 includes one antenna per subcarrier frequency for a total of N antennas 126, 126', 126''.

The digital complex symbol generator 102 generates a vector, e.g., set of N digital complex symbols, of $\{\theta_k, A_k, f_k\}$, for k=1, …, N for each multi-tone symbol duration. The set of complex symbols $\{\theta_k, A_k\}$ for k=1, …, N

includes the portion of the received data to be transmitted during a single symbol duration.

The digital complex symbol generator 102 may include several functional blocks, e.g., to generate information bits to be transmitted, to encode the information bits with channel coding, to interleave the encoded bits, and to map the bits to complex symbols with a modulation constellation. Such functional blocks can be constructed with the technologies known in the art and are thus not shown in Figure 1.

Each complex symbol $\{\theta_k, A_k\}$ corresponding to frequency f_k output by the symbol generator 102 is supplied to a corresponding periodic signal generator 120, 120', 120'' of the periodic signal generator module. Each periodic signal generator 120, 120', 120'' is used to independently process one complex symbol using a periodic signal of a given frequency f_k. Thus, at any given time, N different periodic signal generators are used to independently process different corresponding ones of the N complex symbols output by the signal generator 102 to generate N periodic signals of different frequencies f_k, where k = 1 to N. While in some embodiments the frequencies f_k are basedband frequencies, in other embodiments, the frequencies f_k are passband ones rather than baseband ones.

In accordance with the present invention, each periodic signal generator 120, 120', 120'' generates a periodic signal $s_k(t)$ for the symbol duration T, where the

frequency is equal to f_k. Each generated periodic signal is represented by the following Fourier series:

$$s_k(t) = \sum_{l=1}^{\infty} A_{k,l} \cos(2\pi l f_k t + \theta_{k,l}), \text{ for } t=[0,T].$$

Preferably, the energy of the fundamental component, $A_{k,1}^2$, is significantly greater than the total energy of all the high-order harmonic components, $\sum_{l=2}^{\infty} A_{k,l}^2$. In addition, preferably the complex symbol θ_k, A_k is modulated on the fundamental component:

$$A_{k,1} = A_k, \theta_{k,1} = \theta_k.$$

In one particular embodiment, the periodic signal generated by each periodic signal generator 120, 120', 120'' is a sinusoid signal, that is, all the high-order harmonic components are equal to zero ($A_{k,l}=0$, for $l=2, 3, \ldots$).

In another exemplary embodiment, the periodic signal generated by each periodic signal generator 120, 120', 120'' is constructed from a basic square wave signal. In one such embodiment the basic square wave function is defined as

$$sqr(f,t) = \begin{cases} 1 & t \in [\frac{2m}{2f}, \frac{2m+1}{2f}] \\ -1 & t \in [\frac{2m+1}{2f}, \frac{2m+2}{2f}] \end{cases}, for \quad m = 0,1,\ldots.$$

Here f is the frequency of the square wave function and t is the time variable. The phase and the amplitude of the generated periodic signal are set to be θ_k and A_k, respectively. Hence, the generated periodic signal can be expressed as: $A_k sqr(f_k, t + \frac{\theta_k}{2\pi f_k})$, for t=[0,T]. Figures 4 and 5 show two square wave signals with different phases which may be generated by periodic signal generators 120, 120', 120'' in accordance with the present invention.

The periodic signal output by each periodic signal generator 120, 120', 120'' is then passed to the corresponding prefix generator 122, 122', 122'' which generates and inserts a prefix in front of the received periodic signal. As illustrated in Fig. 6, each signal to be transmitted comprises a prefix portion and a periodic signal portion. In a continuous transmission mode, successive signals representing different symbols are transmitted one after another. For example, Fig. 6 shows that symbol 0 and symbol 1 are two successive symbol durations and the prefix portion of symbol 1 follows immediately after the periodic signal portion of symbol 0.

Traditional OFDM systems sometimes use a cyclic prefix to cover channel transient response. Such conventional prefixes each comprise a single part, e.g., a cyclic prefix portion. Each prefix of the present invention is of sufficient duration that it covers at least the channel transient response. However, in accordance with the present invention the prefix is extended beyond the amount needed to cover the channel's transient

response, e.g., beyond the duration of a conventional cyclic prefix, in order to maintain phase continuity in the transition between two successive multi-tone symbols. Accordingly, a prefix of the present invention includes multiple parts or portions, one to cover the channel's transient response and at least one other part or portion used, e.g., to maintain phase continuity. Various methods for generating a prefix, e.g., a multi-part prefix, in accordance with the present invention will be discussed in detail below with reference to Figures 7 to 11.

In the Fig. 3A system, the output of each prefix generator 122, 122', 122'' is supplied to a corresponding filter 124, 124' 124''. The filters 124, 124', 124'' are used to control, e.g., out-of-band spectral emissions. Filters 124, 124' and 124'' are optional and may be omitted if desired. Alternatively, in place of filters 124, 124' 124'', or in addition to said filters, a set of N separate amplifiers may be used to independently amplify the individual signals corresponding to each of the N tones.

The signal corresponding to each tone output by filters 124, 124', 124'' or the signal output by the prefix generator module 122, 122', 122'' in the case where the filter module is omitted, are supplied to corresponding antennas 126, 126', 126'' which transmit the signals corresponding to each tone of the multi-tone signal to the channel 112. In a wireless system, the channel would be the air.

In accordance with the various exemplary embodiments of the invention, the signals, e.g., including

a periodic signal portion and prefix portion, for all the N tones in a multi-tone signal are not combined within the transmitter. Instead, as illustrated in the Fig. 3A embodiment, the signals of individual tones are transmitted to the channel through independent antennas and combined in the channel itself. In the exemplary wireless system of Fig. 3A, the signals corresponding to the N tones of the multi-tone signal are combined naturally over the air.

In the exemplary Fig. 3A embodiment, each of the signals of distinct tones are transmitted by different antennas. In such an embodiment, the number of independent antennas used by the multi-tone transmitter is equal to the number of tones to be transmitted as part of the multi-tone signal to be broadcast.

In another embodiment, e.g., the embodiment illustrated in Fig. 3B, the set of N tones which comprise a multi-tone signal are divided into several tone subsets. The signals of each tone subset are first combined within the transmitter, and then individually transmitted to the channel. The signals of different tone subsets are combined in the channel. The number of independent antennas needed by the multi-tone transmitter is therefore equal to the number of tone subsets, which is less than the number of tones to be transmitted.

The system 101 illustrated in Fig. 3B is similar to the system 100 of Fig. 3A. However, in the system 101, the signals corresponding to the N tones are grouped into M tone subsets, $M \geq 1$, with the signals in each of the M tone

subsets being combined into a single signal prior to transmission. In the Fig. 3B embodiment, a combining module 130 which comprises M combining units 135, 135', one for each of the M tone subsets, is used to combine the signals of each tone group into a single signal prior to transmission. In one exemplary embodiment, the combining unit is an adder. Note that the antenna array 140 used in the system 101 includes M antennas 145, 145' as opposed to N antennas, where M<N. The signals broadcast by the M antennas combine in the communications channel 112 to form the multi-tone signal being broadcast.

Figure 7 illustrates the construction of a prefix in accordance with one embodiment of the present invention. As discussed above, each of the N prefix generators 122 operate in parallel to generate prefixes for the symbols being transmitted using the individual tones.

As described above, a signal representing an entire symbol to be transmitted comprises a prefix and a periodic signal portion. The prefix, in accordance with the invention includes multiple parts, e.g., two parts.

The 1^{st} part of a prefix, referred to herein as a 1^{st} prefix part, is used to cover channel transient response, thereby simplifying the channel equalization procedure in the receiver. The 1^{st} prefix part maybe the same as, or similar to, the cyclic prefix used in traditional OFDM systems and can be constructed by cyclically extending the periodic signal portion. Thus, methods for constructing the 1^{st} prefix part, e.g., cyclic

prefix generation techniques, are known to the art and will not be discussed further herein.

In accordance with the present invention, the 2nd prefix part is inserted in front of the periodic signal portion, e.g., ahead of the cyclic prefix portion, to continuously connect the end of a previous symbol and the beginning of the 1st prefix part of the current symbol. This use of the 2nd prefix part reduces or eliminates potential discontinuities in the transition between two successive symbols thereby reducing out-of-band spectral emissions that might otherwise occur.

The present invention contemplates several methods for constructing the 2nd prefix part.

In one embodiment, as illustrated in Figure 8, the periodic signal portion of an immediately previous symbol is cyclically extended from the left into the 2nd prefix part of the current symbol, and the extended portion is attenuated by a windowing function. In addition, the 1st prefix part of the current symbol is also cyclically extended from the right into the 2nd prefix part, and the extended portion is attenuated by another windowing function. The two extended portions are then added together to become the 2nd prefix part of the current symbol. First and second filters included in each of the prefix generators 122, 122', 122" may be used to perform the windowing functions with an adder included in each of the prefix generators being used to perform the adding operation. The prefix generators 122, 122', 122'' may also

include cyclic prefix generation circuitry for generating the cyclic prefix portion of a multi-part prefix.

In another embodiment, illustrated in Figure 9, the 2^{nd} part prefix is constructed by a periodic signal, whose frequency may be different from any tone f_k. The frequency and the phase of the new periodic signal is chosen to maintain phase continuity between the end of the previous symbol and the beginning of the 2^{nd} prefix part, and between the end of the 2^{nd} prefix part and the beginning of the 1^{st} prefix part.

Consider symbol 1 in Figure 9 to be the current symbol. Denote T_1 and T_2 respectively the lengths of the 1^{st} and the 2^{nd} parts of the prefix. Suppose the phase at the end of the periodic signal portion of symbol 0 is $\theta(0)$, and the phase at the beginning of the periodic signal portion of symbol 1 is $\theta(1)$. The frequency of the tone in symbol 1 is f_k. Then at the beginning of the 1^{st} part prefix the phase is $\theta(1) - 2\pi f_k T_1$. The frequency f'_k used in the the 2^{nd} part prefix satisfies the following equation:

$$2\pi f_k' T_2 = [\theta(1) - 2\pi f_k T_1 - \theta(0)] \bmod 2\pi \ .$$

There are infinitely many solutions of the above equation. In one particular embodiment f'_k is selected to minimize out-of-band spectral emission. In such an embodiment, the phase of the periodic signal in the 2^{nd} prefix part is such that the phase at the beginning of the 2^{nd} part prefix is equal to $\theta(0)$.

In some embodiments, the multi-tone transmitter 100, 101 transmits several consecutive sets of symbols using the same set of tones and then migrates to a different set of tones. Such systems are referred to as dwell systems. In such systems the term dwell is used to refer to the period of time for which the tone set is left unchanged.

In some dwell system embodiments, one periodic signal generator 120, 120' or 120'' is used to generate the same f_k during an entire dwell with one antenna being used to transmit the periodic signals of the same f_k for all the symbols in the entire dwell.

In such a system, for two successive symbols to be transmitted with tone f_k within a dwell, the constellation of the latter symbol maybe, and in one embodiment is, clockwise rotated by $2\pi(T_1+T_2)f_k$. For example, suppose that QPSK (Quadrature Phase Shift Keying) is used for modulation and that symbol 1 follows immediately after symbol 0 within a dwell. Figure 10 illustrates the constellation of those two symbols.

In dwell system embodiments, generally the symbols in a dwell can be all phase-rotated by a given amount without degrading system performance, for example, when differential modulation schemes are used across the dwell. In such an embodiment, constructing the first symbol in the dwell can be simplified as follows: The 2nd prefix part is constructed by cyclically extending the 1st prefix part without using a different frequency. Meanwhile, a

phase rotation $\Delta\theta$ is added to all the symbols in the dwell such that the phase of the beginning of the 2^{nd} prefix part of the first symbol in the current dwell is equal to the phase of the end of the last symbol in the previous dwell.

Figure 11 illustrates the construction of the first symbol in the dwell and the determination of phase rotation amount. Suppose symbol 1 is the first symbol of the current dwell, and symbol 0 is last symbol of the previous dwell. The frequency of the tone in symbol 1 is f_k. Denote the phase at the end of symbol 0 to be $\theta(0)$, and the phase at the beginning of the periodic signal portion of symbol 1 to be $\theta(1)$ before phase rotation $\Delta\theta$ is added. The prefix (1^{st} and 2^{nd} parts) of symbol 1 is constructed by cyclically extending the periodic signal portion. Phase rotation $\Delta\theta$ to be added to all the symbols in the dwell is given by the following equation:

$$\Delta\theta = \theta(0) + 2\pi f_k (T_1 + T_2) - \theta(1) .$$

Each of the periodic signal generators in the periodic signal generator module 104 include circuitry for generating periodic signals in accordance with the above described techniques of the present invention. Such circuitry may include, e.g., sinusoidal signal generators and squarewave generators. It may also include circuitry for making symbol selections and performing phase rotations on constellations from which symbols may be selected in accordance with the above described techniques. Processors, e.g., CPUs and memory including useful information such as phase shift amounts, etc and/or

computer instructions in the form of a program used to control a processor, may also be used to implement the periodic signal generators. In a similar manner, each of the prefix generator circuits 122, 122', 122'' include circuitry for generating and prepending multi-part prefixes to periodic signals in accordance with the various above described methods. A processor and a computer program may, and in some embodiments is, used to implement the prefix generators 122, 122', 122''. In some embodiments the periodic signal generator module 104, prefix generator module 106 and filter module 108 are implemented as part of a single digital signal processor circuit.

Notably, the power efficient OFDM transmission techniques are well suited for use in portable devices, e.g., notebook computers, PDAs etc. In various embodiments, the transmission systems of the present invention illustrated in Figs. 3A and 3B, with the exception of the antenna array, are mounted inside the housing of a portable device and powered by the portable devices power supply, e.g., a battery.

Numerous variations to the above described methods and exemplary embodiments may be made without departing from the scope of the inventions described herein. For example, while the use of multiple antennas for the transmission of a multi-tone signal are described, a single antenna may be used instead with all the tones being combined prior to broadcasting. In such an embodiment, multi-part prefixes and other features of the invention may still be used.